

HADRONS IN DENSE MATTER^a

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Physical reason behind the mass-shift of vector mesons (ρ , ω , ϕ) in nuclear matter is discussed in the Walecka model and in QCD sum rules. Using analytic formulas for the mass-shift valid at low densities, it is shown that the energy dependent part of the self-energy in medium (wave function renormalization) is a main source for the negative mass-shift, while the energy independent part (the plasma frequency) has relatively a small effect. Future experiments in GSI ($\pi^- + A \rightarrow X + \omega$) and KEK-PS ($p + A \rightarrow X + \phi$) to detect the twin peak structure of vector mesons in e^+e^- spectrum are reviewed. Also, it is proposed a new possible experiment using a $S(\text{strangeness}) = 1$ vector meson $K^*(892)$ with its radiative decay $K^{*+}(892) \rightarrow K^+ + \gamma$.

1 Introduction

Recently, medium modification of hadrons acquires a lot of attention both in theories and experiments (see reviews¹.) Recent CERES data showing a large enhancement of the e^+e^- pairs in central S+Au collisions with 200GeV/A give an experimental hint for such medium effect and induce theoretical studies².

In this talk I will concentrate on the phenomena at zero temperature with finite baryon density, and discuss if there is a significant medium modification on the light vector mesons (ρ, ω, ϕ, K^*) in nuclear matter and nucleus. The answer is affirmative theoretically as will be explained below. I also discuss recent proposed experiments in GIS and KEK to detect such effects in hadron-nucleus reactions, and propose a new experiments using the radiative decay of $K^*(892)$.

2 Vector Meson Poles in Medium

Let us first study general properties of the vector meson propagator $D_{\mu\nu}$ in nuclear matter. For simplicity, I take a vector meson at rest ($\mathbf{p}=0$). Then, the longitudinal and transverse parts become degenerate and the propagator reduces to

$$D_{\mu\nu}(\omega^2) \propto \frac{1}{\omega^2 - m^2 - \Sigma(\omega^2)} , \quad (1)$$

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where ω , m and Σ denote the frequency, the mass in the vacuum, and the self energy in medium, respectively. The exact dispersion relation is obtained by $D^{-1} = 0$ which gives a vector meson pole inside the medium as $\omega = m^*$.

To extract more physics from eq.(1), let us derive an approximate dispersion relation by assuming that Σ is a smooth function of ω near the origin: $\Sigma(\omega^2) \simeq A + B\omega^2$. Also, let us further assume that the density of the system is low enough so that Σ can be treated as a perturbation. Whether the first assumption is valid or not is not known in QCD and depends on models to evaluate Σ . The second assumption is valid at least at sufficiently low density. Under these assumptions, one obtains an approximate dispersion relation

$$(1 - B) \omega^2 - m^2 - A = 0, \quad (2)$$

which gives an approximate pole

$$m^{*2} \simeq m^2 + A + m^2 B. \quad (3)$$

The sign and magnitude of A and B depend on the system one treats. For the photon propagation in a degenerate electron gas, $m = 0$, $A = e^2 n_e / m_e > 0$ and $B = 0$. Namely, m^* represents the well-known plasma frequency. On the other hand, in QCD, there is a possibility that $A > 0$ and $B < 0$ with $A + m^2 B < 0$, i.e. the decreasing vector meson mass in medium. In the following sections, we will demonstrate this explicitly in two different approaches (the Walecka model and QCD sum rules).

3 Pole Shift in the Walecka Model

Let us take the ω meson at rest in nuclear matter. The on-shell properties of the ω -meson in the Walecka model with vacuum polarization were first studied by Saito, Maruyama and Soutome, and by Kurasawa and Suzuki³. Also, good physical arguments were given later by Jean, Piekarewicz and Williams⁴.

In the Walecka model, the validity of the expansion $\Sigma(\omega^2) \simeq A + B\omega^2$ can be checked explicitly, and the neglected terms are found to be $O(m^2/4M^2) \simeq 15\%$ or higher. (M is the nucleon mass.) A (B) in eq.(2) calculated within this approximation comes from the coupling of the ω -meson to the particle-hole excitation (nucleon-anti-nucleon excitation). Then, the ω -meson pole in nuclear matter at low density reads

$$m^{*2} \simeq m^2 + A \left[1 - \frac{4m^2}{3\pi m_\sigma^2} \frac{g_\sigma^2}{4\pi} \right], \quad (4)$$

where $A = g_\omega^2 \rho / M$ (plasma frequency) with $g_\omega(g_\sigma)$ being the $\omega(\sigma)$ -nucleon vector (scalar) coupling constant, and m_σ being the σ -meson mass in the Walecka model. Because of the large and negative contribution originating from B (the term proportional to g_σ^2), the pole shift is negative, $m^* - m < 0$.

The sign of A and B can be understood easily by quantum mechanical level-repulsion due to the second order perturbation. A comes from the coupling of the

ω -meson to the low-lying particle-hole continuum. Thus A must be positive due to the level-repulsion. B comes from the coupling of the ω -meson to the high-lying $N\bar{N}$ continuum. Since the continuum threshold decreases because of the decreasing nucleon's scalar-mass in the Walecka model, the coupling becomes stronger in the medium than in the vacuum. This causes negative B .

Up to now, we have derived an approximate formula which is only valid when the system is in low densities and simultaneously the expansion by $(m/2M)^2$ is valid. In ref.⁵, one can see numerical results obtained by solving the full dispersion relation $\omega^2 - m^2 - \Sigma(\omega^2) = 0$ for ρ and ω mesons. One finds that there is a considerable non-linearity, and the approximate formula (4) is valid only up to $(0.2 \sim 0.3)\rho_0$. Nevertheless, the physics extracted from eq.(4) is qualitatively right. Generalization of this approach to the neutron matter and asymmetric nuclear matter has been also done⁶.

Several comments are in order here.

1. Since $m^* < m$ is mainly caused by the short distant $N\bar{N}$ excitation, one may derive an effective mesonic action by contracting the nucleon-loop into a point in the coordinate space. This gives an effective lagrangian $\mathcal{L}_{eff} \propto \sigma^n F_{\mu\nu}^2$ with σ being the scalar field and $F_{\mu\nu}$ being the field-strength tensor for the ω -meson. Because of the baryon number conservation, one cannot generate an explicit mass term such as $\sigma^n \omega_\mu^2$ from the nucleon loop. This feature may be considered to be consistent with the phenomenological analyses by Friman and Soyeur⁷ on the near-threshold photo-production of ρ and ω mesons.
2. For the ρ -meson, one can imagine considerable collisional broadenings from the processes such as $\rho + N \rightarrow \Delta$, $\Delta + \pi$. This has been checked, and it was shown that there is no significant effect from the collisional broadening near and below ρ_0 as far as the pole position m^* decreases in medium⁸.
3. Since the $N\bar{N}$ excitation only modifies the wave function renormalization part of the propagator B , the behavior of the vector meson propagator has peculiar ω^2 dependence. For example, near the pole position, it has a form $D(\omega^2 \sim m^{*2}) \simeq A/(\omega^2 - m^{*2})$, while at $\omega^2 = 0$, it becomes $D(\omega^2 = 0) \simeq 1/(-m^2)$. Namely, the vacuum mass m instead of m^* appears near $\omega^2 = 0$.
4. Unfortunately, the Walecka model is not a consistent effective field theory of QCD, since it has no expansion parameter which can control the higher dimensional operators of hadron fields unlike the case of the chiral perturbation theory. Also, the effect of the meson-baryon form factors in the $N\bar{N}$ loop could largely attenuate the reduction of m^* . Therefore, it is rather tempting to try more fundamental approaches to the problem. The QCD sum rules and the lattice QCD are the two promising candidates. The latter, however, has still problems to do simulations with finite chemical potential μ although there may be a way out⁹. So, we will review the results of the first approach in the next section.

4 Pole Shift in QCD Sum Rules

The QCD sum rules (QSR) can be regarded as energy weighted sum rules which are familiar in atomic and nuclear physics. A consistent formulation of the QSR in medium was first developed by Hatsuda and Lee¹⁰.

For the vector mesons, the starting point is a two point current correlation function in nuclear matter

$$\Pi_{\mu\nu}(\omega^2) = i \int d^4x e^{i\omega t} \theta(t) \langle [\bar{q}\gamma_\mu q(x), \bar{q}\gamma_\nu q(0)] \rangle_\rho, \quad (5)$$

with $\langle \cdot \rangle_\rho$ denotes an expectation value in nuclear matter with density ρ . A set of sum rules (finite energy sum rules) can be derived from the above definition together with the short distant operator product expansion in QCD. The result is

$$\int_0^\infty ds s^n [\text{Im}\Pi(s) - \text{Im}\Pi_{pQCD}(s)] = C_n \langle \mathcal{O}_n \rangle_\rho. \quad (6)$$

Here $\Pi_{pQCD}(s)$ is a correlation function calculated in perturbative QCD, C_n is a Wilson coefficient and \mathcal{O}_n is a local operator such as $\bar{q}q$, $\bar{q}\gamma_\mu D_\nu q$, $(\bar{q}q)^2$. By making an ansatz $\text{Im}\Pi(s) = Z\delta(s - m^{*2}) + \text{continuum}$, one can extract the pole position and residue in the medium using the information on the matrix elements of local operators.

Eq.(6) applied in the vacuum gives an approximate formula for the ρ and ω meson masses¹¹

$$m^2 \simeq \left[\frac{448}{27} \pi^3 \alpha_s \langle \bar{q}q \rangle_0^2 \right]^{1/3}, \quad (7)$$

where relatively small contribution from the gluon condensate is neglected. In the low density medium, one can derive an approximate formula $m^{*2} \simeq m^2 + A + m^2 B$ with

$$A = 2\pi^2 \frac{\rho}{M} \left(1 - \bar{x} \frac{M^2}{m^2} \right) > 0, \quad (8)$$

$$m^2(1 + B) = m^2 \left(\frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle_0} \right)^{2/3} - 4\pi^2 \frac{\rho}{M_N} \bar{x} \frac{M_N^2}{m^2} < m^2, \quad (9)$$

where the first (second) term in the right hand side of eq.(9) comes from the 4-quark condensate (the twist 2 matrix element). \bar{x} denotes the quark momentum fraction in the nucleon which is measured in the deep inelastic scattering. The gluon condensate, mixed quark-gluon condensate and a dimension 6 condensate with twist 2 are neglected in the above formula. Also, a factorization assumption for the 4-quark condensate in medium is adopted.

Because of the smallness of the plasmon-like term $A > 0$ compared to $B < 0$, m^* generally decreases in nuclear matter. Also, the formula without A and \bar{x} has a similar structure with that predicted by Brown and Rho¹² where KSFRF relation is assumed to be valid in medium. .

The formulas eq.(8,9) are valid only at low densities, and one should solve the full sum rules eq.(6) numerically to get quantitative predictions. The key parameter for such calculation is the ratio of the quark condensate in matter and that in the vacuum. The exact expression for such ratio in QCD reads¹³

$$\frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle_0} = 1 - \frac{\rho}{f_\pi^2 m_\pi^2} \left[\Sigma_{\pi N} + m \frac{d}{dm} (E(\rho)/A) \right]. \quad (10)$$

Here $\Sigma_{\pi N} = 45 \pm 10$ MeV is the pion-nucleon sigma term, and E/A is a nuclear binding energy per particle with m being the current quark mass. The nuclear binding effect is known to be rather small around and below ρ_0 ¹⁴. Using the results of numerical calculation and fitting them by a linear form, one obtains

$$\frac{m_{\rho,\omega}^*}{m_{\rho,\omega}} = 1 - (0.16 \pm 0.06) \frac{\rho}{\rho_0}, \quad \frac{m_\phi^*}{m_\phi} = 1 - (0.023 \pm 0.011) \frac{\rho}{\rho_0}. \quad (11)$$

The errors in the above formulas are originating from the uncertainties of the density dependent condensates. The contribution of the quark-gluon mixed operator with twist 4, which may possibly weaken the mass shift¹⁰, is neglected in the above. Also the validity of the factorization assumption for the 4-quark condensate used in the above should be checked by other method.

I should emphasize here that the formulas eq.(11) does not imply that the density dependence of m^* is strictly linear. The actual numerical results in^{10,16} show non-negligible non-linearity of $m^*(\rho)/m$ below ρ_0 .

Some comments are in order here.

1. Asakawa and Ko have introduced a realistic spectral function by taking into account the width of the ρ -meson and the effect of the collisional broadening due to the π - N - Δ - ρ dynamics¹⁵. By the similar QSR analyses as above, they found that the negative mass shift persists even in this realistic case. The width of the rho meson in their calculation decreases as density increases, which implies that the phase space suppression from the $\rho \rightarrow 2\pi$ process overcomes the collisional broadening at finite density. Further examination of this interplay between the mass shift and the collisional broadening for the ρ -meson is important in relation to the future experiments.
2. Monte Calro based error analysis was applied to QSR by Jin and Leinweber¹⁶ in place of the Borel stability analysis employed in¹⁰. They found $m_{\rho,\omega}^*/m_{\rho,\omega} = 1 - (0.22 \pm 0.08)(\rho/\rho_0)$ and $m_\phi^*/m_\phi = 1 - (0.01 \pm 0.01)(\rho/\rho_0)$, which are consistent with eqs. (11) within the error bars.
3. Very recently Koike and Hayashigaki re-analyzed the effective scattering amplitude \bar{f}_{VN} defined by $m^{*2} \simeq m^2 + \bar{f}_{VN} \cdot \rho$ using the QSR in the vacuum¹⁷. This analysis shows that (a) the previous calculation by the same author¹⁸ is

incomplete (as has been already pointed out in ^{10,16}), and (b) a negative scattering length is obtained; $\bar{f}_{VN} < 0$. The latter feature supports the decreasing vector meson masses. The decrease obtained in ¹⁷ for ρ and ω mesons are factor 2 smaller than that in ¹⁰. This is partly because the Borel stability of the scattering length calculation is not as excellent as that of the QSR in medium, and partly because the scattering-length approach gives a formula only valid at extremely low density. In fact the number obtained in ¹⁷ is consistent with that of the numerical result of $m^*(\rho)/m$ near $\rho = 0$ given in Fig.2(a) of ¹⁰ and in Fig.1 of ¹⁶.

4. Jaminon and Ripka has reached a similar pole shift by using a model of vector mesons coupled to constituent quarks ¹⁹. Saito and Thomas have examined a different but comprehensive model (bag model combined with the Walecka model) and found decreasing vector-meson masses ²⁰; $m_{\rho,\omega}^*/m_{\rho,\omega} \sim 1 - 0.09(\rho/\rho_0)$. The spectral shift of the quarks inside the bag induced by the existence of nuclear medium plays a key role in this approach.
5. The three momentum \vec{p} dependence of the dispersion relation $\omega^2 = m^{*2} + (1+a)\vec{p}^2$ of the vector-meson in QSR has been also studied recently by Lee and Friman ²¹. They found that $|a| < 0.08$ at nuclear matter density. Walecka model also predicts small a . ²²
6. Eletskii and Ioffe has analysed an “effective mass” of the rho-meson passing through the nuclear matter ²³. Since their approach is limited only to the fast rho-mesons having the kinetic energy more than 2 GeV, it does not have direct relevance to the physics discussed in this article.

Basic idea common in the approaches predicting the decreasing meson mass (at rest) may be summarized as follows. In nuclear matter, scalar (σ) and vector (ω) mean-fields are induced by the nucleon sources. These mean-fields give back-reactions to the nucleon propagation in nuclear matter and modify its self-energy. This is an origin of the effective nucleon mass $M^* < M$ in the relativistic models for nuclear matter. The same mean-fields should also affect the propagation of vector mesons in nuclear medium. In QSR, the quark condensates act on the quark propagator as density dependent mean-fields. In the Walecka model, the coupling of the mean-field with the vector mesons are taken into account through the short distant nucleon loop with the effective mass M^* . An interesting observation is that major part of the mean-field contributes to modify the wave function renormalization constant B as shown in (4) and in (9).

5 Possible Experiments

How one can detect the spectral change of vector mesons in experiments? As have mentioned in the Introduction, enhancement of the lepton pairs below the ρ -resonance

region in S+Au collisions was reported by CERES/NA45 at CERN²⁴. Similar enhancement of the muon pairs is reported in S+W collisions by HELIOS-3 at CERN too²⁵. This enhancement is rather difficult to explain by conventional mechanisms of the lepton pair production such as the Dalitz decay, $\pi^+\pi^-$ annihilation and the ρ -decay². Although the assumption of the decreasing ρ -mass can explain the data well², it is not an unambiguous proof of the mass shift because complicated dynamics of the heavy-ion collisions are involved in the data analyses.

In higher energy heavy ion collisions such as RHIC and LHC, high temperature plasma with low baryon density will be formed in the central region. In this case, the twin peak structure of the ϕ -meson proposed by Asakawa and Ko²⁶ is a very interesting and clean signature of the mass shift.

On the other hand, around the normal nuclear matter density at zero temperature, one could see the mass shift in various hadronic or electromagnetic production of the vector mesons with heavy nuclear target. A typical signal of the mass shift in these cases is the twin peak structure similar to the one that Asakawa and Ko proposed.

Suppose that one creates the vector meson inside the nucleus by π , K , γ or p beams. The total number of lepton pairs from the decay of vector mesons inside the nucleus is roughly estimated as

$$N_{in}(e^+e^-) \simeq N \times (1 - e^{-\Gamma_{tot}^* R}) \times \text{Br}(e^+e^-), \quad (12)$$

where N is the total number of created vector mesons, Γ_{tot} is the total width of the vector meson in the nucleus, R is the nuclear radius, and $\text{Br}(e^+e^-)$ is a branching ratio to the e^+e^- decay. The second factor in the right hand side of eq.(12) is a probability to have vector mesons decaying inside.

Some comments are in order here.

1. One can *effectively* increase the number of vector mesons decaying inside the nucleus by choosing a kinematics of producing “recoilless” or “stopped” vector mesons.
2. The particle width in nuclear matter Γ_{tot}^* can be quite different from the width in the vacuum Γ_{tot} given in Table 1. The collisional broadening increases the total-width, while the decreasing m^* tends to make the total-width small due to the phase space suppression. Unfortunately, we do not know exactly how Γ_{tot}^* behaves as a function of nuclear density. If $\Gamma_{tot}^* \sim \Gamma_{tot}$ (which may be quite wrong), most of the ρ (ϕ) mesons decay inside (outside) the nucleus. On the other hand, because of its large (small) width, the invariant mass spectrum of lepton pairs is broad (sharp). The situation for ω meson is just in between ρ and ϕ .
3. To get clean signals with small final state interactions, the detection of the lepton pair is the better than $\pi^+\pi^-$ or K^+K^- , although the branching ratio is as small as $10^{-4} \sim 10^{-5}$. Despite the strong final state interactions, the radiative decays and hadronic decays of the vector mesons can be also used as signals.

Table 1: Vector Mesons below 1 GeV and its total width, leptonic branching ratio, radiative $K\gamma$ branching ratio, and proposed experiments.

particle	Γ_{tot}	$\text{Br}(e^+e^-)$	$\text{Br}(K\gamma)$	Proposed experiment
ρ^0 (770) $\bar{u}u - \bar{d}d$	$(1.3\text{fm})^{-1}$ ($\pi\pi$)	4.5×10^{-5}	--	Spring-8 $\gamma+A$ ($E_\gamma < 2.5\text{GeV}$)
ω (782) $\bar{u}u + \bar{d}d$	$(23.5\text{fm})^{-1}$ ($\pi\pi\pi$)	7.2×10^{-5}	--	HADES at GSI π^-+A ($p_\pi \sim 1.3\text{GeV}/c$)
ϕ (1020) $\bar{s}s$	$(45\text{fm})^{-1}$ (KK)	3×10^{-4}	--	E325 at KEK-PS $p+A$ ($E_p \sim 12\text{GeV}$)
K^* (892) e.g. $\bar{s}u$	$(3.9\text{fm})^{-1}$ ($K\pi$)	0	1×10^{-3} $K^{*+} \rightarrow K^+\gamma$	

4. $K^{*+}(892)$, which is a $S(\text{strangeness}) = 1$ vector meson, does not decay into lepton pairs but decays into $K^+\gamma$ with sizable branching ratio of 10^{-3} (see Table 1). This meson has several advantages: (a) The total width is 50 MeV which is sufficiently large for K^* to decay in heavy nuclei and is sufficiently small to get clean signal in $K^+\gamma$ spectrum. (b) The branching ratio of K^* to $K^+\gamma$ is order of magnitude larger than the leptonic branching ratios of neutral vector mesons. (c) Because the final product K^+ has quark composition $\bar{s}u$, K^+ has a long mean free path in nuclear matter ($5 \sim 6$ fm) and does not suffer final state interactions so much. Thus, $K^{*+}(892)$ supplies a new possibility of detecting the mass shift, which has not been addressed so far. Studies of pole shift of K^* in the Walecka model and in QCD sum rules as well as its detectability in heavy-ion collisions and hadron-nucleus collisions are now under way²⁷.

There is a proposal of detecting the e^+e^- pairs from the reaction $\pi^- + A \rightarrow X + \omega$ using HADES at GSI²⁸. The typical momentum of the incident π^- is 1.3 GeV/c, which can create substantial number of “almost” recoilless ω mesons inside the nucleus (e.g. $p_\omega < 0.4\text{GeV}/c$). This will give rise to a distinct twin ω peak structure as well as shifted broad ρ -peak in the lepton pair spectrum.

In E325 experiment at KEK²⁹, the reaction $p + A \rightarrow X + \phi$ are used and e^+e^- as well as K^+K^- will be measured. The incident proton energy is 12 GeV which gives the typical ϕ -meson momentum 1 GeV/c. Still, one can see a twin peak structure in heavy nuclei: the higher peak is the ϕ decaying outside and the lower peak is from the ϕ decaying inside. The change of the leptonic vs hadronic branching ratio $r = \Gamma(\phi \rightarrow e^+e^-)/\Gamma(\phi \rightarrow K^+K^-)$ can be also measured. Since m_ϕ is very close to $2m_K$ in the vacuum, any modification of the ϕ -mass or the K -mass changes the ratio r substantially as a function of mass number of the target nucleus.

One can also do the similar experiments in SPRING-8 in Japan using $\gamma+A$ reactions

³⁰.

6 Concluding Remarks

The spectral change of the elementary excitations in medium is an exciting new possibility in QCD. By studying such phenomenon, one can learn the structure of the hadrons and the QCD ground state at finite (T, ρ) simultaneously. Theoretical approaches such as the QCD sum rules and the hadronic effective theories predict that the light vector mesons (ρ , ω , ϕ , K^*) are sensitive to the partial restoration of chiral symmetry in hot/dense medium. These mesons are good probes experimentally, since they decay into lepton pairs which penetrate the hadronic medium without losing much information. Thus, the lepton pair spectroscopy in QCD will tell us a lot about the detailed structure of the hot/dense matter, which is quite similar to the soft-mode spectroscopy by the photon and neutron scattering experiments in solid state physics.

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